WAVELENGTH-AGILE OPTICAL SENSOR FOR EXHAUST PLUME AND CRYOGENIC FLUID INTERROGATION*

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ABSTRACT

Two optical sensors developed in UW-Madison labs were evaluated for their potential to characterize rocket engine exhaust plumes and liquid oxygen (LOX) fluid properties. The plume sensor is based on wavelength-agile absorption spectroscopy. A device called a chirped white pulse emitter (CWPE) is used to generate the wavelength agile light, scanning, for example, 1340 – 1560 nm every microsecond. Properties of the gases in the rocket plume (for example temperature and water mole fraction) can be monitored using these wavelength scans. We have performed preliminary tests in static gas cells, a laboratory GOX/GH_2 thrust chamber, and a solid-fuel hybrid thrust chamber, and these initial tests demonstrate the potential of the CWPE for monitoring rocket plumes. The LOX sensor uses an alternative to wavelength agile sensing: two independent, fixed-wavelength lasers are combined into a single fiber. One laser is absorbed by LOX and the other not; by monitoring the differential transmission the LOX concentration in cryogenic feed lines can be inferred. The sensor was successful in interrogating static LOX pools in laboratory tests. Even in ice- and bubble-laden cryogenic fluids, LOX concentrations were measured to better than 1% with a 3 μs time constant.

INTRODUCTION

The sensor system described here is based on absorption spectroscopy and a new device known as a Chirped White Pulse Emitter (CWPE). The CWPE emits "white" (broadband) pulses of light that can be "chirped" (arranged into fast wavelength scans that cover a broad spectral range such as 1340 – 1560 nm). The rapid-wavelength scanning (or wavelength-agile) laser beam is directed through the environment of interest. By rapidly monitoring broad absorption spectra, the CWPE can interrogate temperature, pressure, and multiple species concentrations in gases at arbitrary conditions. Along a line-of-sight with non-uniform properties, the CWPE can also record gas temperature distributions rather than just the path-averaged temperature. Liquids can also be measured with the CWPE. These capabilities represent a dramatic enhancement of the best fiber-optic sensors available just two years ago. Such sensors were generally capable of path-averaged, single-species concentration and temperature measurements, and only in low-pressure gases.

Rugged, accurate, and fast-response optical sensors for propulsion system diagnosis have been sought for more than a decade. Building on initial work in flames [1], the tunable diode laser (TDL) made steady progress toward enabling this goal. The sensing approach is depicted in Figure 1. Wavelength-tunable light (typically fiber-coupled) is projected through gas- and/or liquid-phase paths of interest. As the laser wavelength is scanned, the spectral signature of the transmitted light is recorded. In this way, many spectra are recorded in succession. The transmission spectra contain detailed information such as the temperature, pressure, and species concentrations along the probed paths [2]. The *steady* progress transformed into *rapid* progress with the emergence of a new class of TDLs known as "wavelength-agile" diode lasers circa 2000. These lasers can rapidly scan over a broad wavelength range. Figure 2 compares the wavelength-scanning characteristics of a standard distributed-feedback (DFB) diode laser with a wavelength-agile vertical-cavity surface-emitting laser (VCSEL). The VCSEL scans about 20 times as far in 1/100th the time, for a total of ~ 2000 times the "wavelength-agility". Wavelength-agile lasers were initially applied to measure temperatures (up to 4000K) and pressures (up to 40 atm) in pulse detonation engines [3], and their tremendous potential for sensing and control in propulsion systems was predicted [4].

Although the ~2 nm scanning range provided by VCSELs represented a dramatic improvement, it was recognized that lasers with a broader scanning range would increase sensor flexibility, accuracy, and ruggedness. In response to this need, a swept-wavelength source offering another 2000× improvement in wavelength-agility [5] was developed at the UW-Madison Engine Research Center. An example configuration of this "chirped white pulse emitter" (CWPE) is shown schematically in Figure 3. The CWPE operates on an entirely different principle than the TDL. Rather than scanning a single laser mode through a wavelength range, the entire wavelength range is generated in a single "white" pulse. The white pulse is then "chirped", or arranged into a wavelength scan by passing it through a long optical fiber. The different wavelengths travel through the fiber at different speeds. Note that 5.5-km of optical fiber occupies a volume of only ~ 300 cm^3 and can be wound around any convenient spool.

Distributuion Statement _

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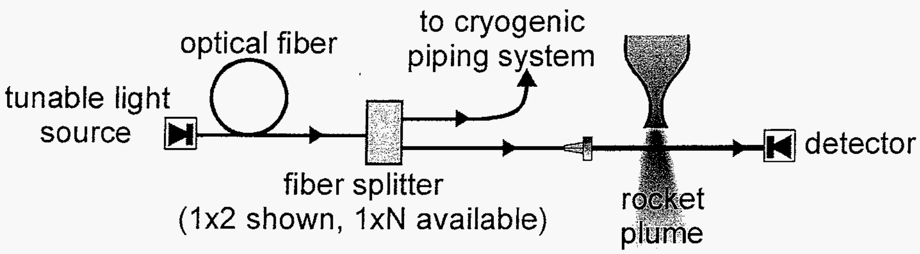


Figure 1. General schematic of sensing approach, illustrating the capacity to measure multiple gas and liquid properties in multiple locations using a wavelength-tunable light source

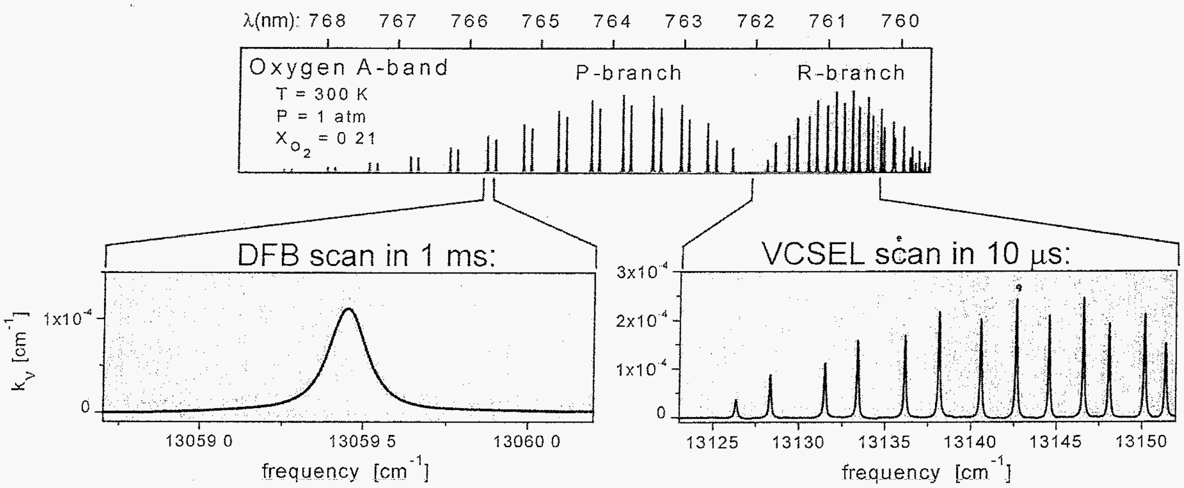


Figure 2. Theoretical O_2 absorption spectrum (upper panel) highlighting measurements (lower panels) performed with standard (DFB) and wavelength-agile (VCSEL) diode lasers

In an initial demonstration, the CWPE was used to measure water vapor, carbon dioxide, acetylene and ethanol contained in a high-pressure gas cell. Sample results are shown in Fig. 4. The measurements shown were acquired in a total time of 20 μs (the system has a characteristic response time of 20 ns, but longer measurement times can be used to average data for increased accuracy). The concentrations of the absorbing species are determined from the area of each feature; the gas temperature and pressure are determined from the shapes of the features. Thus, the spectra recorded in the 20 μs interval yields several pieces of information: temperature, pressure, and species concentrations. In the next 20 μs, another spectrum is obtained and the gas properties are updated. Thus, continuous records of relevant properties can be recorded with fast time response.

An alternative CWPE design is shown in Fig. 5. In this case, current pulses are injected into an LED to create pulses of "white" light. These pulses are then processed as before to perform wavelength-agile absorption spectroscopy. Note that the acetylene absorption spectrum shown in Fig. 5 contains more structure than the one shown in Fig. 4. This is primarily because the longer fiber (18 km instead of 5.55 km) increases the duration of each wavelength scan, which in turn results in increased spectral resolution.

METHOD OF APPROACH

The chirped white pulse emitter (CWPE) was originally planned for combined interrogation of rocket plumes and LOX systems. However, initial tests and simulations revealed that a different strategy would be preferred for LOX systems. Thus, the CWPE was reserved for plume and reaction zone measurements, and a wavelength-multiplexed strategy was developed for LOX measurements. Here we discuss the two sensors.

Although perhaps not as "optically harsh" as rocket plumes, LOX systems present their own challenges to optical sensing. Thus the LOX sensing technique we chose is also based on rapidly obtaining information at multiple wavelengths. It is a "differential absorption" technique that has been proposed by several researchers but to the best of our knowledge has not been published in the open literature. A LOX absorption spectrum shown in Fig. 6. reveals a broad absorption feature near 630 nm. Using two lasers, our approach is to measure the difference between absorption near 630 nm and absorption near 640 nm to quantify the LOX content along a line of sight.

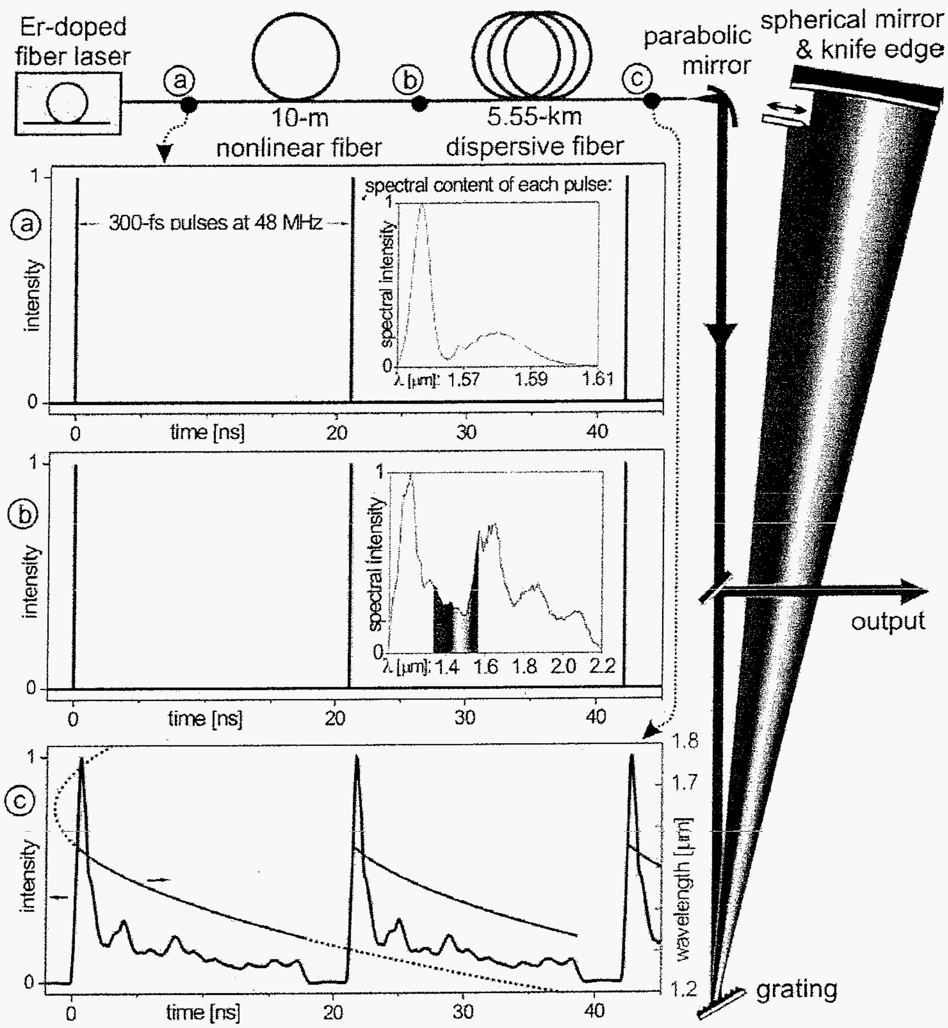


Figure 3. Schematic of CWPE configured to scan 1350-1550 nm every 20 ns, including performance data measured at locations (a), (b), and (c)

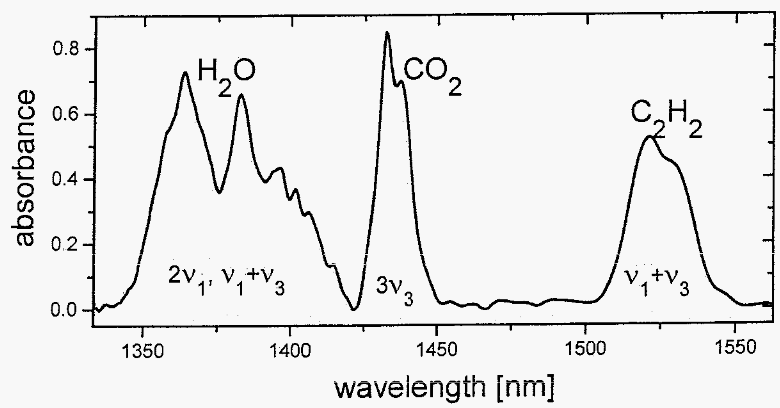
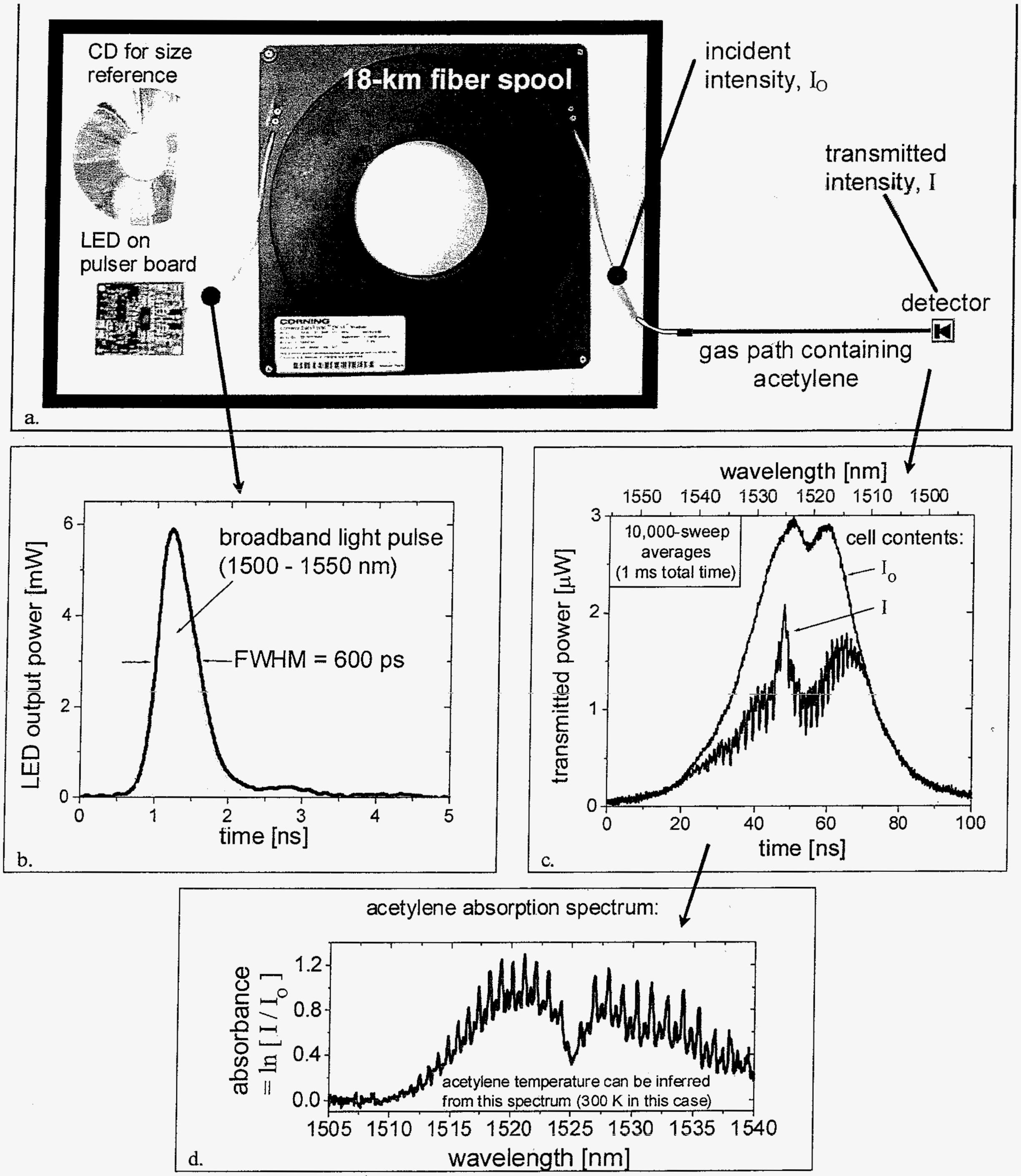


Figure 4. Spectra measured in a 184 cm-long cell at T = 330 K, P = 10 bar. Gas composition: X_{H2O} = 0.005, X_{CO2} = 0.99, X_{C2H2} = 0.005. Measurements are an average of 1000 consecutive scans obtained in 20 μs total time (each scan takes 20 ns)



The process for collecting an acetylene absorbance spectrum. Part a diagrams the experimental set up. Part b shows the initial power signal from the LED using a current pulse of 1A peak. Part c demonstrates how the pulse broadens and distributes spatially by wavelength after traveling the length of the fiber. Part c also shows the intensity of the pulse after traveling through the acetylene path. Finally, part d shows the spectrum that is produced by applying Beer's law (absorbance = -ln(I/Io) to the data shown in part c.

Figure 5. The process for collecting an acetylene absorbance spectrum

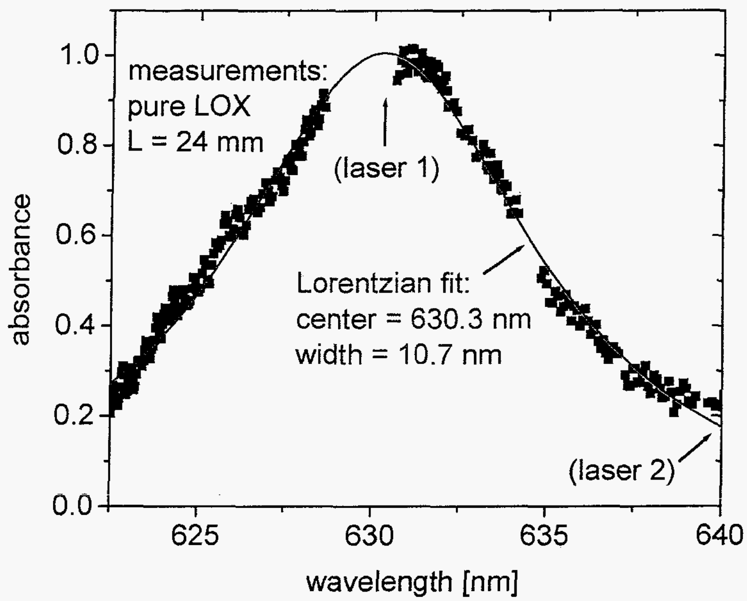


Figure 6. LOX absorption spectrum near 630 nm

Our approach is shown schematically in Fig. 7. Two fixed-wavelength lasers are coupled into the same optical fiber. The power of each laser is modulated sinusoidally at ~ 500 kHz through the injection current. The two sinusoids are programmed out-of-phase and balanced so that their combined power sums to a constant. Their combined power is delivered to the probe volume using fiber optic components and monitored with a detector. One laser wavelength is chosen near an absorption maximum of LOX (~630 nm) and the other laser wavelength is chosen near an absorption minimum (~640 nm). Thus, when LOX enters the probe path, one of the sinusoidal components is preferentially attenuated, and the detector then registers a sinusoidal signal. The amplitude of the detected sinusoid can be monitored using sensitive lock-in amplification techniques and related to the concentration of LOX in the probe path. Bubbles or other interfering media entering the probe path generally affect both wavelengths similarly. By normalizing the lock-in output by the total power registered at the detector, the effects of such interferences can be reliably removed. Thus, using the simple and robust setup as shown in Fig. 7, LOX concentrations can be monitored with excellent accuracy. The amount of pressurizing nitrogen, for example, can then be quantified from the reduction in LOX concentration in the probe path.

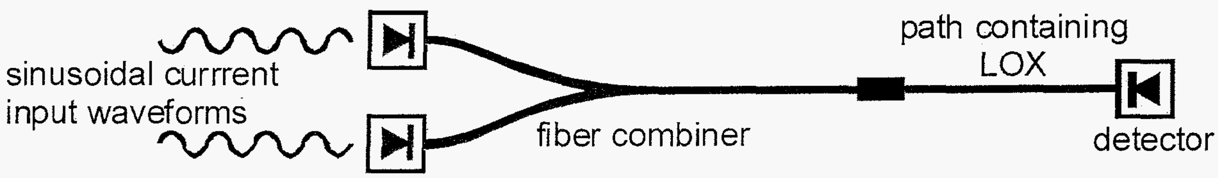


Figure 7. The differential absorption spectroscopy approach

RESULTS AND DISCUSSION

The two sensor systems discussed above were tested by interrogating combustion zones and laboratory LOX systems. The rocket thrust chamber tests were conducted at ORBITEC's small rocket test facility, and included both hybrid and gas-gas thrust chambers. The hybrid rocket burned a paraffin-based solid fuel and gaseous oxygen, while the gas-gas chamber employed oxygen and hydrogen. The LOX interrogation tests were conducted at the University of Wisconsin-Madison.

<u>ROCKET THRUST CHAMBER TESTS</u>

Some initial tests were performed to assess the suitability of the CWPE to rocket plume tests. A simple and insightful test involves measuring the raw transmission of a laser beam projected through a rocket engine plume. The wavelength of the laser beam is chosen to be "nonresonant": not absorbed by rocket plume gases. A sample transmission trace recorded in the plume of an ORBITEC hybrid rocket engine operating on oxygen and paraffin-based solid fuel is shown in Fig. 8. A typical firing of this hybrid rocket thrust chamber is shown in Figure 9. A 62.5

μm diameter collection fiber was used to record this transmission trace; this is the largest-diameter fiber that can be coupled to the high-speed detector needed for monitoring the CWPE output.

As can be seen in Figure 8, losses in transmission due to beam steering or attenuation by particulates in the plume can be kept below 5%, at least in this relatively small-scale rocket plume. A 5% modulation in intensity would mask the transmission signatures of gas-phase absorption if the sensor was not wavelength-agile; however, the 100-ns CWPE scans are fast enough that the modulation is nearly constant during an individual scan. *Thus, these results demonstrate that the CWPE is well-suited to plume measurements.* Depending on the location of the beam in the rocket plume and on the amount of particulate present, losses can be greater than 5%. However, as long as the losses are kept below 99% and the losses do not vary on nanosecond timescales, we expect the CWPE to be well-suited to rocket plume measurements.

To further demonstrate the potential for CWPE testing in exhaust plumes, we performed some measurements with an off-the-shelf tunable laser (New Focus 6327). This laser can scan from 1380 nm to 1480 nm in ~ 3 s. This relatively slow tuning is not considered wavelength-agile and is not ideal, but when rocket tests can be run in an approximately steady mode for > 3 s, the laser is able to capture useful absorption spectra. We did this to demonstrate the potential of absorption spectroscopy in rocket environments. One of the advantages of using a slow-scanning laser is that a larger detector can be used (detector time response increases with decreasing size). In turn, a larger diameter collection fiber can be used, which reduces the transmission noise. Recall that above we obtained a 5% transmission noise with a 62.5 μm collection fiber. With a 550 μm collection fiber, the transmission noise drops to < 0.5%.

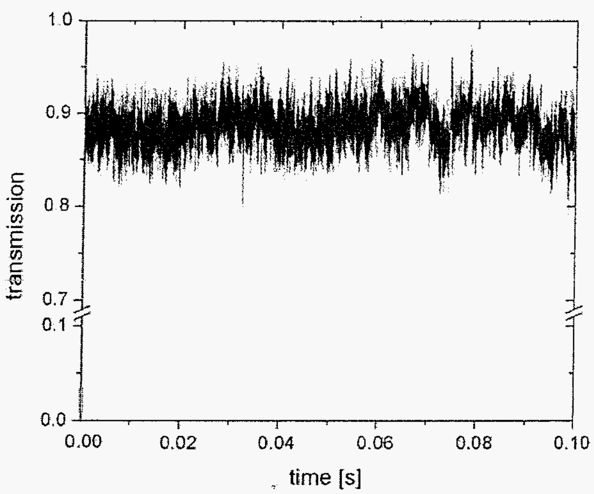


Figure 8. Transmission trace through an oxygen-hydrocarbon exhaust plume similar to that shown in Figure 9

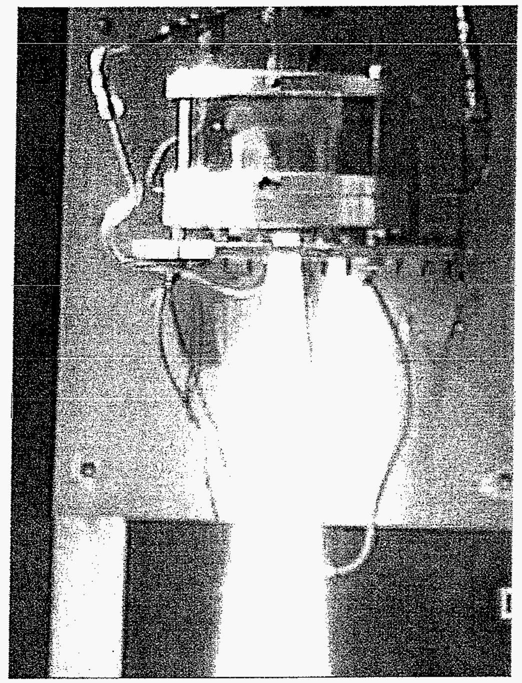


Figure 9. Typical system check-out test firing of a lab-scale hybrid rocket burning gaseous oxygen and paraffin-based solid fuel in ORBITEC small-rocket test facility (thrust ~50 lb_f, chamber pressure ~200 psia)

The slow-scanning laser measurements were performed in the combustion chamber itself. Figure 10 shows a schematic of one of ORBITEC GOX/GH_2 vortex combustion chambers that was outfitted with a quartz tube to allow for optical access to the reaction zone. This particular chamber (with quartz) was typically operated at about 30 lb_f of thrust and a chamber pressure of about 120 psia. An augmented spark igniter was used to achieve ignition. Figure 11 shows a typical test firing with GOX and GH_2 at a mixture ratio of about 6. Notice that the reaction zone is clearly visible in the center of the quartz chamber. The location of the laser diagnostic support ring is also indicated in the right side of the figure.

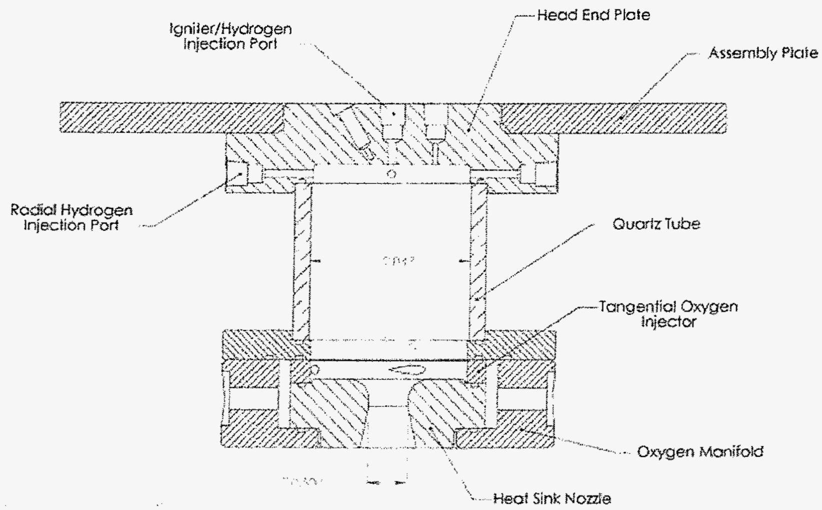


Figure 10. GOX/GH_2 vortex combustion chamber

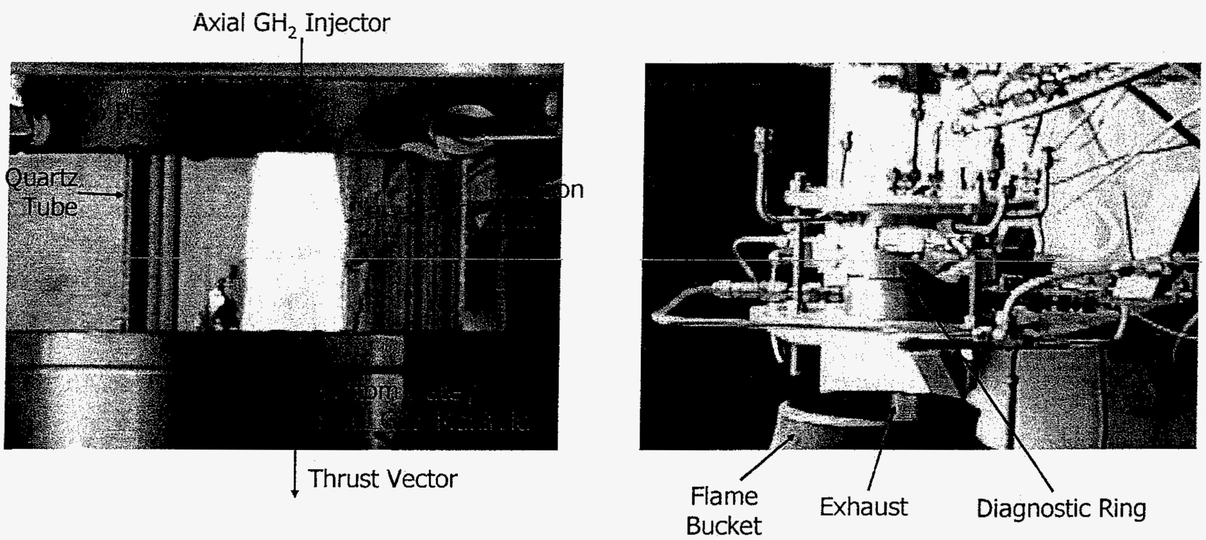
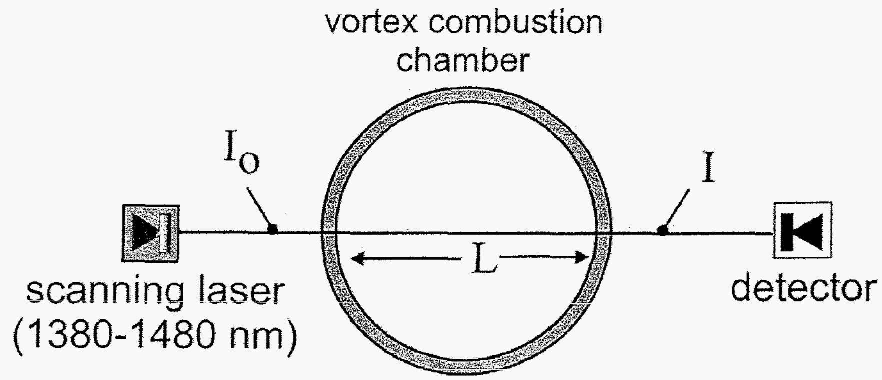


Figure 11. Hot firing showing combustion chamber reaction zone in quartz tube (left) and thrust chamber on test stand (right) with laser diagnostic ring

Figure 12 shows a schematic of the slow-scanning laser diagnostic system wherein a single beam from a scanning laser is passed through the quartz combustion chamber, through the O_2/H_2 reaction zone, and onto a detector. The laboratory experiment is shown in Figure 13 and indicates the laser beam (in the input fiber optic cable), the diagnostic ring support mounted around the quartz tube, and the output fiber optic cable that feeds the detector. During the hot firing (see Fig. 11), which typically lasts for approximately 5 seconds, the laser diagnostic system was activated to test the feasibility of this type of system. A sample absorption spectrum recorded in ~ 3s with this slow-scanning laser is shown in Fig. 14. The CWPE is expected to actually perform much better than the slowly-tunable laser, and the rocket plume will be an easier location to probe than the combustion chamber. However, even with these more challenging constraints, the Fig. 14 H_2O absorption spectrum exhibits excellent signal-to-noise ratio. This data is for a single line-of-sight through the center of the combustion chamber. When multiple lines-of-sight are recorded, tomographic reconstruction can be used to obtain planar images of gas temperature and H_2O concentration from such data.

LABORATORY TESTS OF LOX SENSOR

Using the approach discussed in section 6, a sensor capable of measuring LOX concentration accurate to ~ 1% with a response time of ~ 3 μs has been developed. The system shown in Fig. 15 has been used to evaluate the sensor. The sensor uses 2 lasers at nominal wavelengths of 630 and 640 nm. The laser beams are combined into a single fiber. The output beam from the fiber is directed into the test environment. The 630 nm wavelength is absorbed much more strongly by LOX than the 640 nm wavelength; thus LOX concentration can be inferred from the differential transmission through the test environment. To simulate dynamic changes in LOX concentration, a test environment based on the spinning mirror shown in Fig. 15 is used. The beam is directed onto the spinning mirror which, in turn, sweeps the beam over a retroreflective staircase submerged in pure LOX. The stairsteps simulate a rapidly changing LOX concentration as the beam sweeps across. The retroreflected surface returns the light to a parabolic mirror which focuses it onto a detector. The rapidly-varying path length caused by the staircase simulates rapidly-varying LOX concentration flowing in a fixed-diameter pipe.



$$\text{Beer's Law:} \quad T_\nu \equiv \frac{I}{I_o} = \exp(-\underbrace{k_\nu}_{f(T,P,X_i)} \cdot L) \quad \textit{if uniform}$$

Figure 12. Schematic of tunable laser diagnostic system

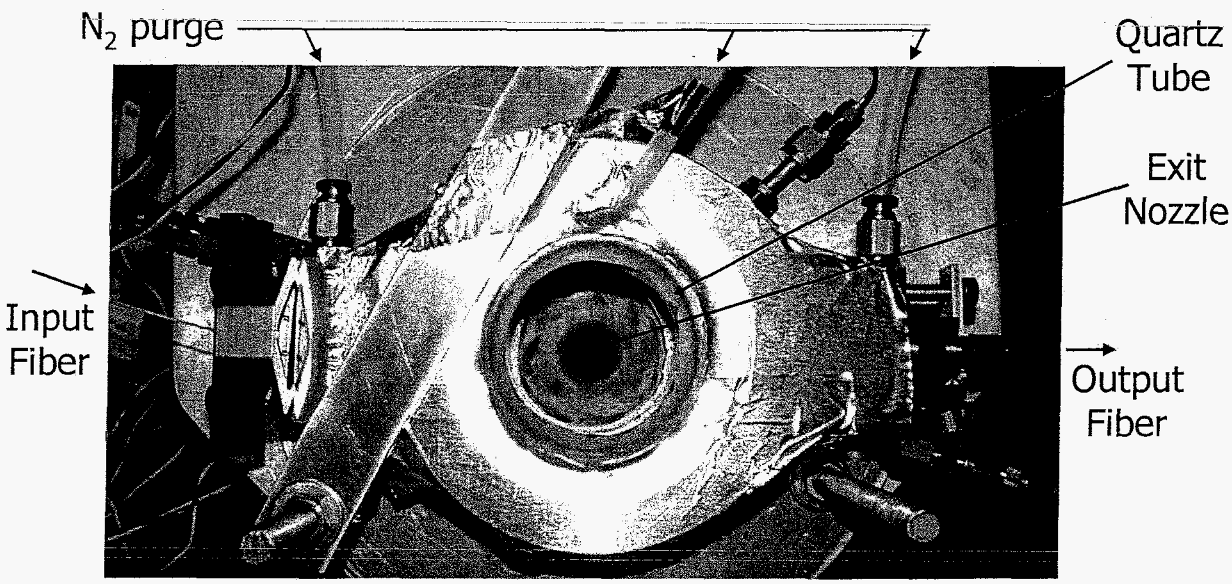


Figure 13. Photograph of laser diagnostic ring mounted around quartz combustion chamber (thrust chamber faceplate removed for clarity, view is from top looking down at exit nozzle)

Sample data recorded using the Fig. 15 setup is shown in Fig. 16. The LOX path length measured by the sensor compares very well with the expected signature from the staircase; the discrepancies are believed to be due to ripples on the surface of the LOX or on the retroreflective surface itself. Each step in the Fig. 16 data represents a ~ 3% change in LOX concentration for the intended application of LOX flowing in a fixed diameter pipe. The ~ 3μs time constant and ~ 1% LOX concentration accuracy are evident in the Fig. 16 results.

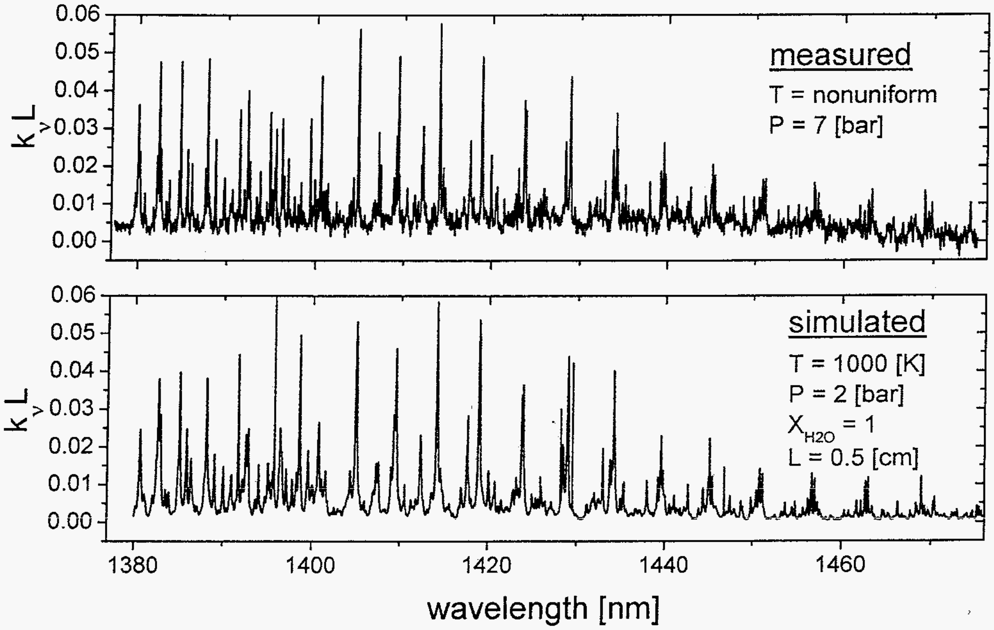


Figure 14. H_2O absorption spectrum measured in an ORBITEC vortex combustion chamber with a laser tuning from 1380-1480 nm in 3 s. The measurement agrees well with a HITRAN simulation in the lower panel

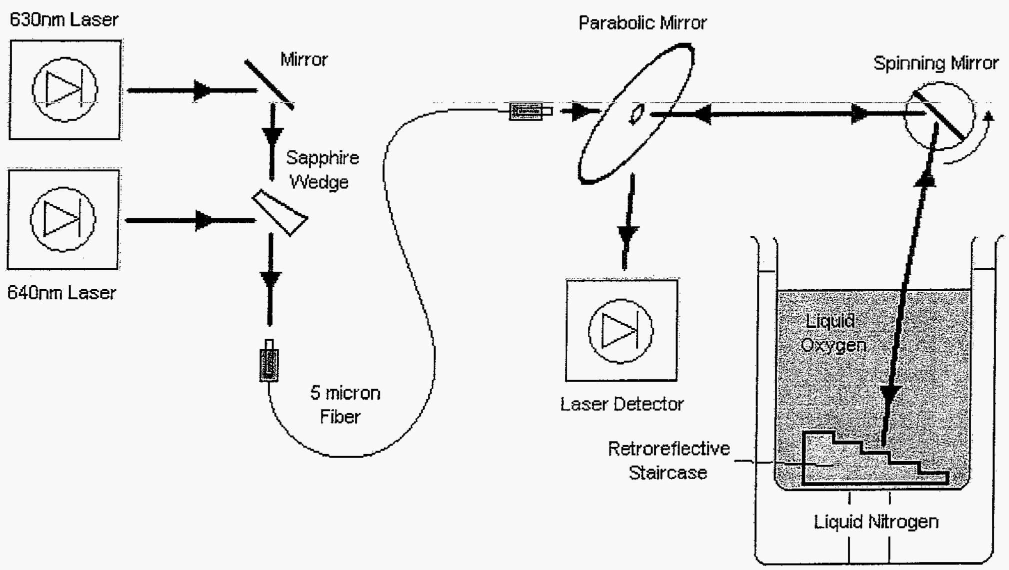


Figure 15. System used to test LOX sensor under dynamic conditions

A test of stability was also done to determine the amount of error introduced into the data over time. These errors could come from a variety of sources, such as drifting laser power. Since it would be difficult to keep the LOX from evaporating for a long time in our test environment, an artificial absorbance of the 630 nm laser was simulated. This was done by reflecting the laser off of a microscope slide before coupling it into the fiber. Also, the spinning mirror was stopped and positioned to project the laser on one spot of the retro reflector for the entire experiment.

As figure 17 shows, the simulated length of 62.3 mm was very stable over the 60-minute period. This indicates that measurements such as the one shown in figure 4 can be reliably made over long periods of time on the order of hours.

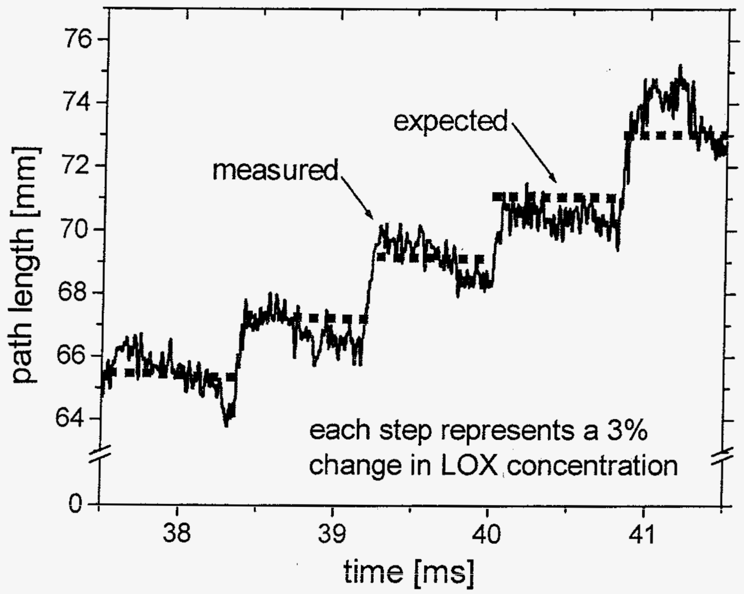


Figure 16. Dynamic LOX sensor data recorded using the Fig. 2-8 setup

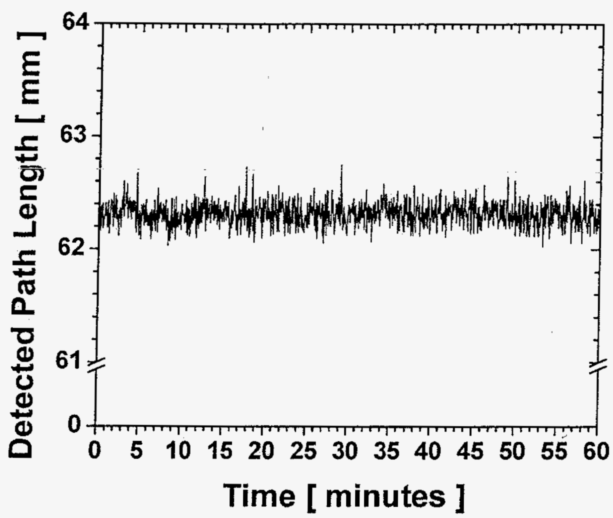


Figure 17: Stability of LOX sensor over the course of one hour

SUMMARY AND CONCLUSIONS

A prototype wavelength-agile optical rocket propulsion sensor (WORPS) system was designed and developed. The WORPS system is composed of a chirped white pulse emitter (CWPE) for rocket plumes and a wavelength-multiplexed sensor for LOX systems. The two sensors have been developed through ongoing tests in UW-Madison labs and ORBITEC facilities. Both sensor systems underwent successful preliminary testing in laboratory rocket combustion zones and LOX reservoirs. In the near future, the WORPS will be modified for improved accuracy and flexibility. A more extensive test program will be conducted to refine the WORPS system.

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